Report for 2003KS33B: A Field Assessment of a Method for Estimation of Ground-Water Consumption By Phreatophytes

- Conference Proceedings:
  - Butler, J.J., Jr., Kluitenberg, G.J., and D.O. Whittemore, A field method for estimation of ground-water consumption by phreatophytes – year one (abstract), Proc. 21st Annual Water and the Future of Kansas Conf., p. 27, 2004.
  - Loheide, S,P., II, Butler, J.J., Jr., and S.M. Gorelick, A modeling evaluation of a method for estimating groundwater usage by phreatophytes (abstract), GSA 2004 Annual Meeting Abstracts with Program, v. 36, no. 5, p. 390, 2004.
  - Whittemore, D.O., Butler, J.J., Jr., Healey, J.M., McKay, S.E., Aufman, M.S., and R. Brauchler, Seasonal and long-term groundwater quality changes in alluvial aquifer systems (abstract), GSA 2004 Annual Meeting Abstracts with Program, v. 26, no. 5, p. 451, 2004.
  - McKay, S.E., Kluitenberg, G.J., Butler, J.J., Jr., Zhan X., Aufman, M.S., and R. Brauchler, In-situ determination of specific yield using soil moisture and water level changes in the riparian zone of the Arkansas River, Kansas, Eos, v. 85, no. 47, Fall Meet. Suppl., Abstract H31D-0425, 2004.
- Other Publications:
  - Butler, J.J., Jr., Groundwater flow in interconnected stream-aquifer systems: From models to the field, an invited presentation to the Department of Geological and Atmospheric Sciences, Iowa State University, March 12, 2004.
  - Butler, J.J., Jr., Loheide, S.P., II, Kluitenberg, G.J., Bayless, K., Whittemore, D.O., Zhan, X., and C.E. Martin, Groundwater consumption by phreatophytes in a mid-continent stream-aquifer system (abstract), Eos, v. 85, no. 17, Jt. Assem. Suppl., p. JA237, 2004.
- Articles in Refereed Scientific Journals:
  - Loheide, S.P., III, Butler, J.J., Jr., and S.M. Gorelick, Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment, Water Resour. Res., in press, 2005.

Report Follows

KWRI PROGRESS REPORT – YEAR TWO

Project Title: A Field Assessment of a Method for Estimation of Groundwater Consumption by Phreatophytes – Year Two
Start Date: March 1, 2004
End Date: February 28, 2005
Investigators and Affiliations: James J. Butler, Jr., Kansas Geological Survey (PI), Gerard J. Kluitenberg, Kansas State University (Co-PI), Donald O. Whittemore, Kansas Geological Survey (Co-PI), Charles J. Barden, Kansas State University (Additional Cooperator), and Craig E. Martin, University of Kansas (Additional Cooperator).
Research Category: Statewide Competitive Grant
Descriptors: phreatophytes, ground water, evapotranspiration, water balance

PROBLEM AND RESEARCH OBJECTIVES

Low streamflows are an increasing problem in Kansas and other areas of the U.S. As a result, smaller amounts of water are available for diversions to water supplies and wetlands, for inflows to reservoirs, for capture by wells in nearby aquifers, for sustaining aquatic wildlife, and for recreation. Stream-aquifer interactions play an important role in the generation and maintenance of low streamflows. Ground-water development in regional aquifers that discharge water to stream corridors and in alluvial aquifers immediately adjacent to streams is often a major factor responsible for low-flow periods. Consumption of ground water by phreatophytes in riparian zones could also be an important factor contributing to periods of reduced streamflow. Reliable estimates of the magnitude of this consumption, however, have not yet been obtained.

In this project, we are developing a method for estimation of the amount of ground water consumed by phreatophytes. This method is being evaluated at a field site of the Kansas Geological Survey at which a great deal of previous work has been performed. The previous work, in conjunction with the additional work to be done as part of this project, enables the methodology development and assessment to be carried out under highly controlled conditions. The end product of this research will be a technique of demonstrated effectiveness for both identifying and quantifying phreatophyte activity. Although the technique will be developed at a site with a mix of phreatophytes common in central Kansas, the approach will be equally viable in areas with different mixes of phreatophytes. The major objectives for this research project are to 1) develop a method for quantifying the consumption of ground water by phreatophytes in hydrologic conditions common to central and western Kansas, 2) evaluate this method at a well-controlled field site, and 3) quantify ground-water consumption by phreatophytes along a portion of the middle reach of the Arkansas River in Kansas. An auxiliary objective of this work is to gather a detailed data set on the major fluxes in stream-aquifer systems that can serve as the basis for research proposals on the quantitative assessment of stream-aquifer interactions in settings common to the Great Plains.

The six specific activities proposed for year two were as follows:

1. Further characterize the Larned Control Volume,

2. Continue monitoring of water and salinity fluxes and phreatophyte activity,
3. Determine phreatophyte water sources by isotopic measurements,
4. Relate water-table fluctuations to phreatophyte activity,
5. Inventory the riparian woodlands of the Arkansas River from Kinsley to Great Bend,
6. Estimate phreatophyte activity along the Arkansas River from Kinsley to Great Bend.

METHODOLOGY

The ultimate objective of this project is to develop a practical approach for quantifying phreatophyte consumption of ground water. This is being done at the Larned Research Site, a field area of the Kansas Geological Survey that is located adjacent to the USGS stream-gaging station on the Arkansas River near Larned in central Kansas (Larned Research Site – Figure 1). Since the late spring of 2001, KGS personnel have done extensive work on stream-aquifer interactions at the Larned site. This previous work enables the tasks of this project to be performed in a controlled field setting.

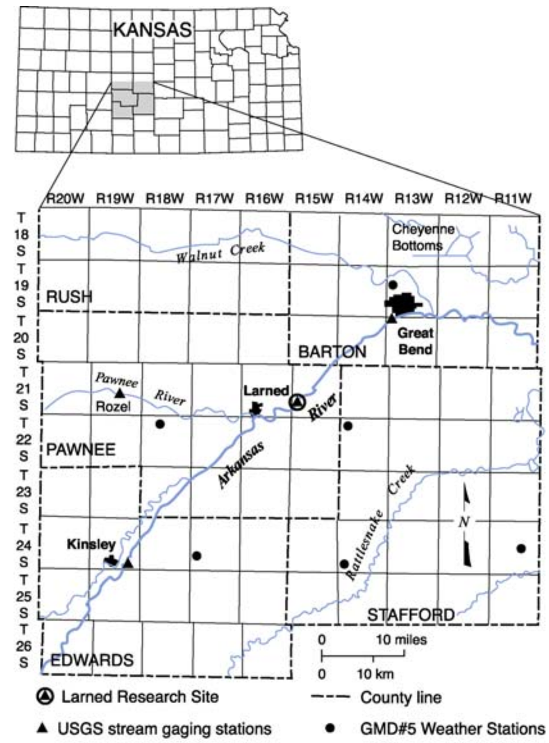


Figure 1

The methods development that is the focus of this work is being done using the control volume concept. A control volume is essentially a very large lysimeter. Water and salinity fluxes into/out of this volume are determined so that the relationship between phreatophyte activity and water-level fluctuations can be assessed (Figure 2). In the first phase of this project, the Larned Control Volume (LCV) was established in the riparian zone just west of the Arkansas River channel. Wells and vadose-zone monitoring equipment were installed within and adjacent to the LCV in May 2003. Two additional wells were added on the west side of the LCV in June of 2004. Direct-push electrical conductivity logging was used for detailed lithologic characterization prior to well installation.

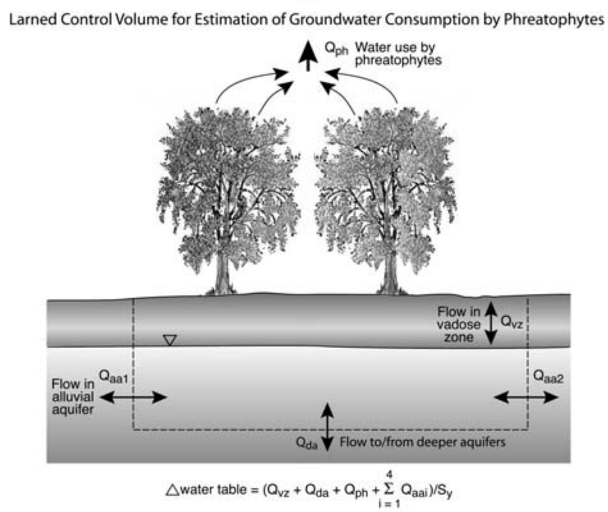


Figure 2

All wells in the LCV are equipped with integrated pressure transducer/datalogger units (In-Situ MiniTroll) that are programmed to take pressure-head readings every 15 minutes. Since the wells in the LCV could be overtopped during periods of high flow, absolute pressure transducers are used instead of the gauge-pressure sensors utilized in most hydrogeologic studies. The absolute-pressure sensors measure the pressure exerted both by the height of the overlying column of water in the well and by the atmosphere. The atmospheric pressure component is removed using data from a barometer at the site. Figure 3 displays records from an absolute-pressure sensor in the riparian zone prior to and after the barometric pressure correction. Manual measurements of water levels in the monitoring wells are taken biweekly during the summer and bimonthly otherwise in order to assess the performance of the pressure sensors and, if necessary, to adjust the calibration parameters.

Additional neutron-probe access tubes were installed adjacent to four of the wells in the LCV in June 2004. The depth of the original access tubes installed in 2003 was 1.83 m. The water table dropped more than anticipated in 2003 so the bottom of those access tubes was a considerable distance above the water table for a portion of the monitoring period. A deeper set of access tubes (3.05 m) was therefore installed in June 2004 to allow monitoring of moisture content over a larger depth range. Measurements in the access tubes were recorded every one to two weeks during the summer with a neutron probe (Model 503 DR Hydroprobe Moisture Depth Gauge; Campbell Pacific Nuclear) using a count duration of 16 s and depth increments of 0.152 m. Standard counts were recorded in the field both prior to and after access tube measurements. The mean standard count for the duration of the study was used to convert each measured count to a count ratio (CR). The soil volumetric water content (m^3 m^{-3}), θ, corresponding to each measured count ratio was calculated with the calibration equation $\theta = 0.2929 \times CR - 0.0117$, which was based on laboratory calibrations and an adjustment for PVC pipe.

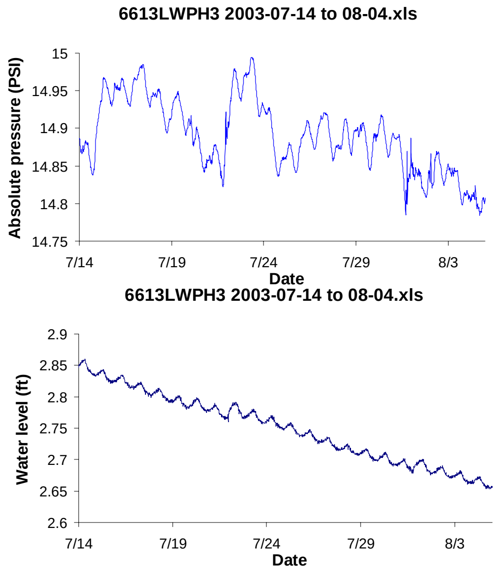


Figure 3

Ground-water samples were collected from all of the shallow wells in the LCV during the spring and early summer, and from a flow event of the Arkansas River, and analyzed for specific conductance and major and minor constituents. Vertical profiles of specific conductance and temperature were measured several times during the summer and monthly to quarterly for the rest of year two in all LCV wells using a YSI Model 30/50 meter and 50 ft cable. Specific conductance and temperature were recorded at the same interval as pressure head in two LCV wells using multiple sensor probes with dataloggers (an In-Situ MP Troll 9000 and a YSI 600SL Sonde).

Transpiration on the leaf scale was measured using a portable photosynthesis system (Li-Cor Li-6400). This machine consists of an infrared gas analyzer (IRGA) that measures the concentration of CO_2 and H_2O in the system air flow. There are two separate IRGA readings, one for the incoming air and one for the air in the sample chamber. A leaf is placed in the sample chamber and sealed inside. The system has its own light source and can control the concentrations of CO_2 and H_2O with the use of soda lime and Drierite, chemicals that scrub the air of CO_2 and H_2O, respectively. For all the measurements taken during this study, the concentration of CO_2 in the sample chamber was 370 PPM. Leaves from cottonwood and mulberry trees were measured under two different light levels and were maintained under conditions approximating ambient during the measurement. The light levels were 1500 μmol photons m^{-2} s^{-1}, which is typical of clear sky light in mid-morning and mid-afternoon during the summer in Kansas, and 300 μmol photons m^{-2} s^{-1}, which is typical for mostly cloudy conditions during the summer. Measurements were taken once a month from June through September 2004. Data were gathered from 7:30 AM to 4:00 PM. Leaves both near the ground and high in the canopy were measured using a cherry picker unit. Data for all of the leaves are in the form of the amount of H_2O transpired per m^2 of leaf area per second at the given light level, temperature and vapor pressure deficit. To extrapolate to the entire canopy, the m^2 leaf tissue per m^2 of ground was estimated using a leaf area index (LAI) sensor. LAI was measured on a biweekly basis during the summer of 2004 between noon and 2 PM. A series of points were selected within the riparian zone and LAI was measured at waist height in the four cardinal directions at each of the points.

Transpiration on the tree scale was measured using sapflow sensors (Thermal Logic [now East 30 Sensors] Model SF18). A sapflow sensor consists of two needles encased in an epoxy head. One needle has an embedded heating element, while the other has three embedded thermocouples. The installation procedure consists of removing a section of bark from the tree, emplacing the needles in the xylem, and covering the exposed xylem and probe with aluminum foil. The heater is turned on for eight seconds every 30 minutes and the temperature at three depths in the xylem above the heater is measured using the thermocouples. Three sensors are equally spaced around the circumference of the tree and remain in the tree for a period of four days. A programmable datalogger (Campbell Scientific 23X) is used to control sensor operation. The velocity of the water flow in the xylem is determined from the time it takes the heat pulse to move past the thermocouples. The volumetric rate of water movement in the trunk is determined from the thickness of the xylem and the velocity measurements. Sapflow measurements were taken every two to three weeks from June to September 2004.

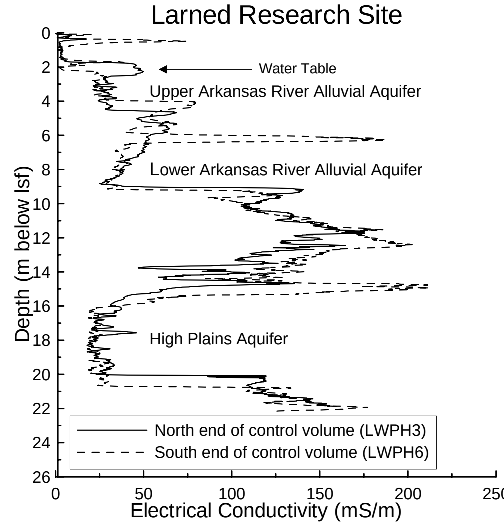
A weather station (Hobo Weather Station logger and sensors, Onset Computer Corp.) was installed within 1600 m of the LCV in June of 2003 and then moved to within 800 m of the LCV in September of 2003. The weather station is equipped with sensors to measure temperature, precipitation, solar radiation, wind speed and direction, and relative humidity. Data are averaged (temperature, solar radiation, wind speed and direction, and relative humidity) or summed (precipitation) and logged at a 15-minute interval. Potential evapotranspiration is calculated from the meteorologic data using the Penman-Monteith equation. The relative humidity sensor was replaced in the summer of 2004 because of damage resulting from a wasp building a nest on the sensor. Fine-mesh netting was placed around the radiation shield to prevent further insect damage.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The principal findings of the second year of the project and their significance will be briefly discussed in the context of the six activities proposed for year two of the project:

Activity 1: Further characterize the Larned Control Volume – two wells and four neutron-access tubes were installed within and adjacent to the LCV. Direct-push electrical conductivity logging was used for detailed lithologic characterization at both well sites. As shown in Figure 4, three aquifer units can be identified in the shallow subsurface within the LCV. The thickness of the sandy silt zone separating the upper and lower portions of the Arkansas River Alluvial Aquifer varies across the site, so the degree of interconnection between these units also varies. The clay and silt zone separating the Arkansas River alluvial aquifer and the High Plains aquifer is consistent across the LCV. Both wells were screened in the upper zone of the Arkansas River alluvial aquifer to the west of the LCV. The purpose of these wells was to provide estimates of the direction and magnitude of lateral flow into the LCV. Slug tests were performed in all water-table wells in the LCV and confirmed the high permeability of the shallow aquifer. Specific yield (S_y) estimates were obtained from an analysis of the neutron logs from both the shallow and deep access tubes. The resulting estimates (S_y=0.19-0.21 for all but one level at the LCV) revealed that specific yield varies relatively little in space. A pumping test performed in the High Plains Aquifer to the west of the LCV in the fall of 2003 was analyzed to provide an estimate of the hydraulic conductivity (2.2×10^{-3} m/d) of the silt and clay zone separating the Arkansas River alluvial aquifer from the High Plains Aquifer.

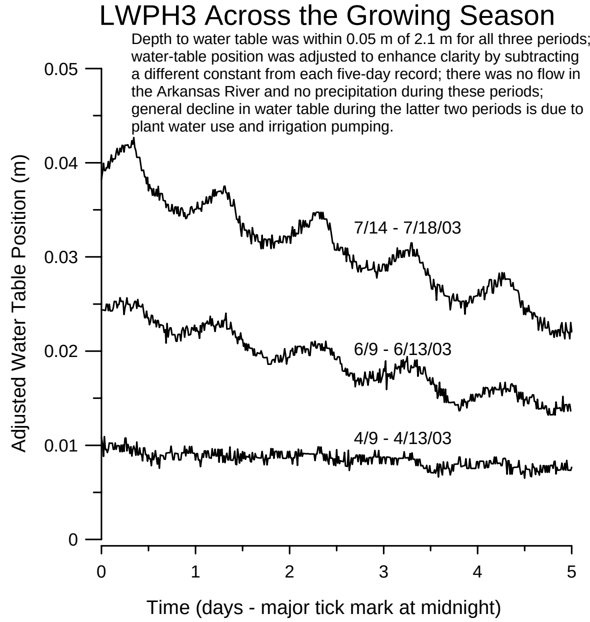
Figure 4
Electrical Conductivity Logs
Larned Research Site



Activity 2: Continue monitoring of water and salinity fluxes and phreatophyte activity – pressure-head measurements were obtained in all wells in the LCV and adjacent areas at 15-minute intervals beginning in the spring of 2003. These measurements clearly show that prominent diurnal fluctuations in the water table are only observed in the growing season (Figure 5) and are limited to the riparian zone (Figure 6). A professional high-accuracy survey of the horizontal and vertical locations of the casing tops was performed in March of 2004, so gradients can now be calculated from the pressure-head measurements.

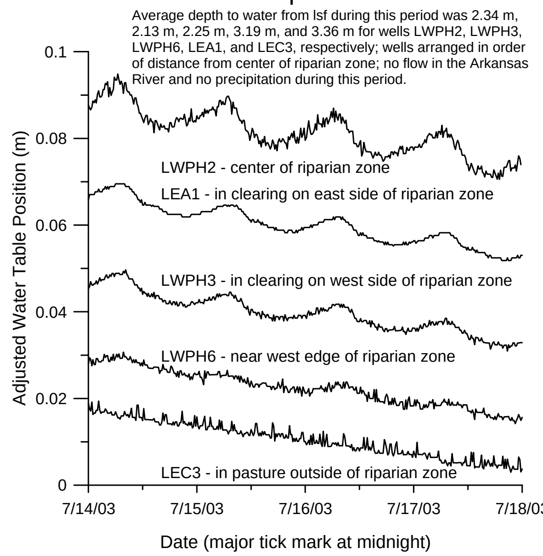
Salinity balance in the LCV was originally planned as an approach for estimating ground-water consumption to compare to and

Figure 5
Water Table Fluctuations at Well
LWPH3 Across the Growing Season



corroborate the water-level fluctuations. The principle for this approach was based on an increase in the total dissolved solids (TDS) content of the water as the trees consumed ground water and left most all of the dissolved solids in the residual water. Results from the study in year one indicated a high degree of heterogeneity in the spatial distribution of TDS (as indicated by water sample analysis and specific conductance data). The attempt to increase the temporal and spatial characterization of the ground-water TDS during year two through both vertical profiling at all LCV wells and continuous conductance recording at two LCV wells showed an even greater level of spatial and temporal heterogeneity than expected. In addition, some of the chemical and conductance data suggest that much of the dissolved solids in the water in the capillary fringe could be precipitated in the unsaturated zone as the water levels dropped. When water levels rise during a river flow event, much of these precipitated salts could be redissolved. The observations indicate that a salinity balance approach to estimating phreatophyte water consumption that is based on ground-water salinity measurements would have too much uncertainty to be valid.

Figure 6
Water Table Fluctuations
Across Riparian Zone



The salinity measurements provided a detailed data set on the major TDS fluxes in the river-aquifer system at Larned that could serve as the basis for research proposals on the quantitative assessment of stream-aquifer interactions – part of the auxiliary objective of the research. The vertical profiles of specific conductance showed the varying influence of flow events in the Arkansas River on the salinity of the ground water in the alluvial aquifer. Figure 7 illustrates the conductance changes at approximately the same elevation in the wells from the late summer 2003 to the fall 2004 during which there were two periods of substantial flow in the Arkansas River. In both instances, the source of the flow was precipitation runoff from the Pawnee River watershed. The figure indicates the large influence that bank storage of the fresher river water had on decreasing the salinity of the shallow ground water. Although there was a general decrease in the influence of the river water on the ground-water conductance with increasing distance from the river for the first flow event (September 2003), there were much more complicated changes in ground-water conductance during and following the second flow event (late June through early July 2004). The data indicate that, although phreatophyte water consumption may cause a general increase in the salinity of the ground water, the salinity changes are controlled more by the movement of different packets of ground water through the heterogeneous alluvial sediments.

The study also discovered that the water-level fluctuations generated by the phreatophytes were sufficient to cause variations in water salinity in the shallow alluvial aquifer during the period of discharge of bank storage input by high river flow, apparently as a result of moving the interface between lower and higher salinity ground water. This is displayed in Figure 8 for a period after the flow event in the Arkansas River of late June to early July 2004. The figure shows that it took a substantial amount of time for the freshest water from the river bank storage to reach the location of well LWPH4A and that this fresher ground water did not move evenly with time to the location. Pronounced oscillations in the conductance in August, which correlated with the water-level fluctuations related to phreatophyte activity, disappeared in late September as the diurnal water-level changes ceased when the phreatophytes became dormant. The substantial spatial and temporal variations in the ground-water salinity based on the vertical profile and continuous observations, and inferred from past river-water quality, have an important bearing on approaches to ground-water sampling for examination of contaminant transport caused by stream-aquifer interactions.

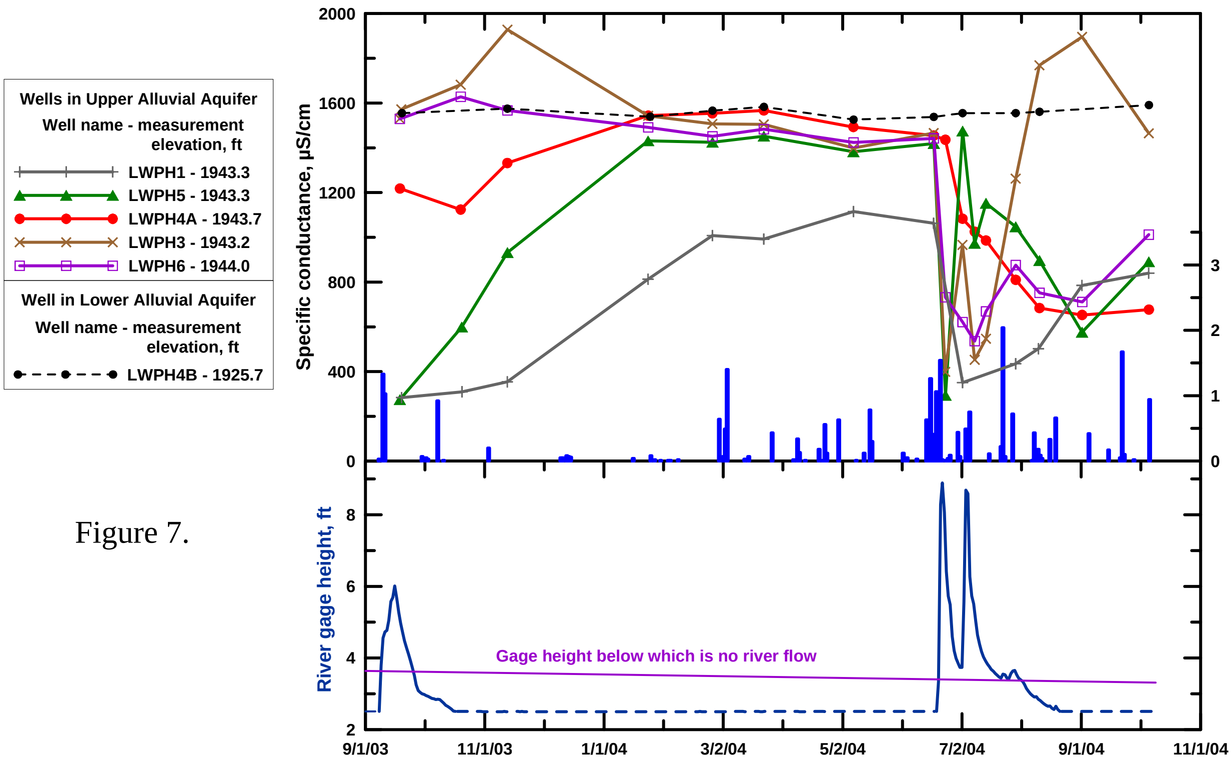


Figure 7.

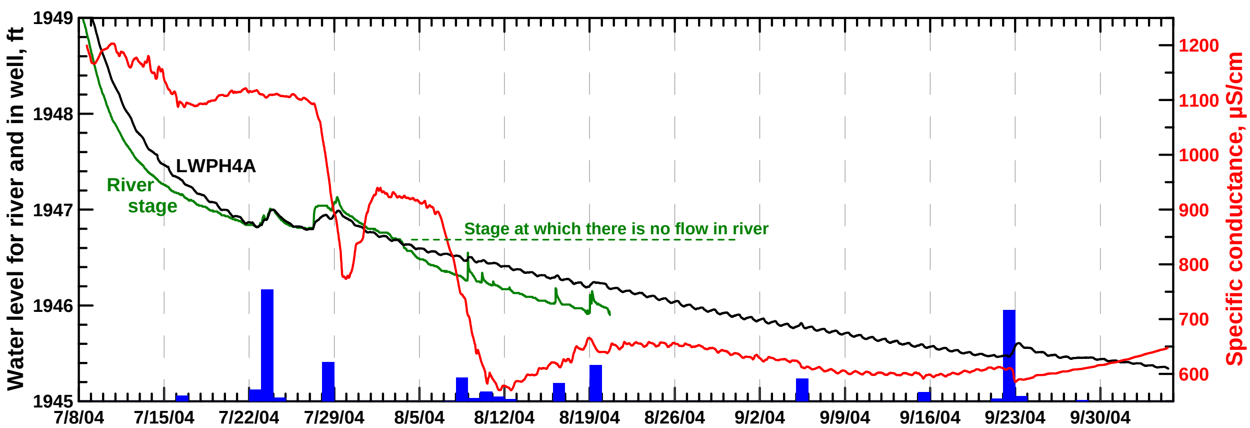


Figure 8. The blue bars are daily precipitation. The highest bar represents 2.04 inches.

Activity 3: Determine phreatophyte water sources by isotopic measurements – water samples have been collected and are awaiting analysis. Those analyses will be performed in year three of this project;

Activity 4: Relate water-table fluctuations to phreatophyte activity – this activity was a major focus of both theoretical and field work in year two. A simulation study of the White method for estimation of ground-water consumption by phreatophytes was completed in year two. In that study, we performed a series of numerical simulations to assess the ramifications of the assumptions underlying the White method and the viability of the resulting estimate of ground-water consumption by phreatophytes. We found that the White method provides reasonable estimates (within 20%) for formations consisting primarily of sands and gravels when the specific yield is defined as the total drainable porosity. However, in finer-grained materials, an estimate of the readily available specific yield must be utilized to obtain reasonable estimates.

In the field, we related sapflow and vadose-zone measurements to the water-table fluctuations to yield new ecohydrologic insights into phreatophyte activity in the LCV. For example, Figure 10a shows plots of the depth to water at well LWPH3 for the same period in late spring of 2003 and 2004. Diurnal fluctuations are imperceptible in the water-level data from June 2004, despite the nearly 50% larger potential for evapotranspiration during that period. The most likely explanation for the absence of fluctuations in the 2004 data is that the water table, which is 0.31 m deeper than in June 2003, is out of reach of the riparian-zone vegetation. Sapflow data collected during these two periods from cottonwoods of similar size and apparent vitality support this explanation, as the 2004 sapflow velocities are greatly reduced relative to those of 2003 (Figure 10b). Neutron-log data from 2004 are consistent with the sapflow and water-level data, as volumetric water content is near the permanent wilting point over most of the vadose zone (not shown). Field notes from a site visit on 6/4/04 by the project PI report yellow leaves on and premature leaf fall from many of the cottonwoods in the riparian zone, indicating that the trees were undergoing stress. The water table was near a historical low in early June 2004, so the most

Figure 10a
Variations in Water-Table Position at Well LWPH3 for Early June of 2003 and 2004

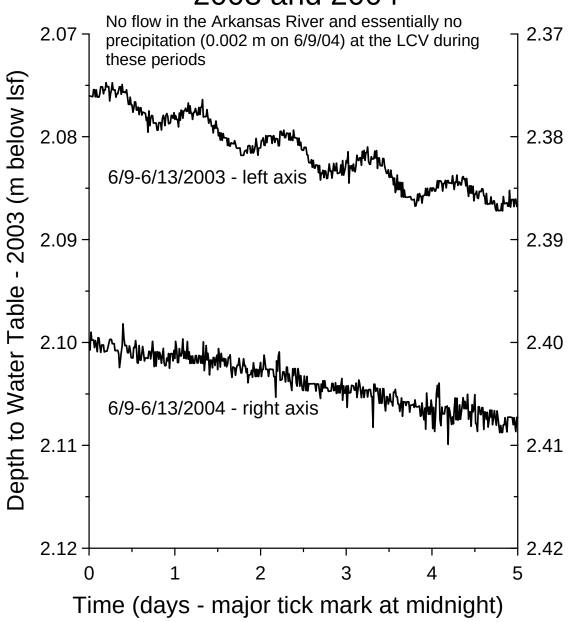
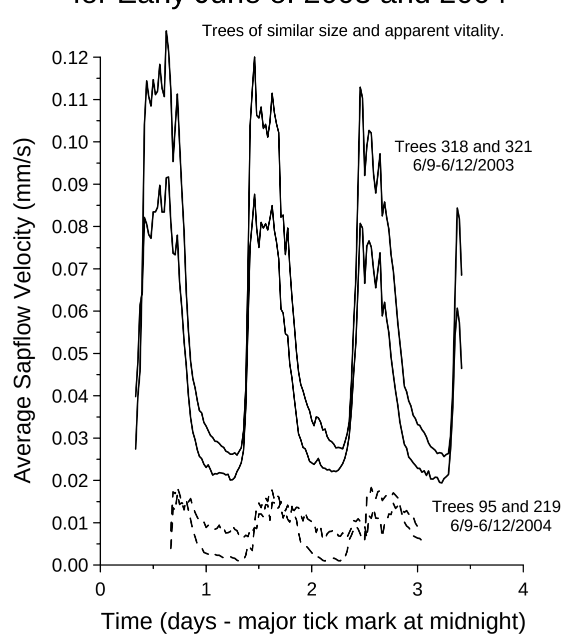


Figure 10b
Variations in Average Sapflow Velocity from LCV Cottonwoods for Early June of 2003 and 2004

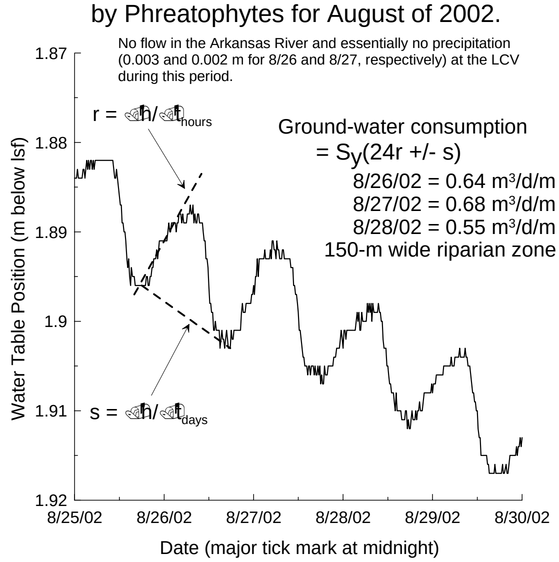


likely explanation for that stress is that the phreatophytes had not had a previous opportunity to develop a root network to extract water from that depth. The phreatophytes at the site do have the capability of drawing water from greater depths, as illustrated by well LEA1 (Figure 6) located on higher ground on the east side of the riparian zone 1.05 m above well LWPH3. However, the trees must have previously developed a root network to extract water from those depths (the water table was also out of reach of vegetation in the vicinity of well LEA1 in early June 2004, but the depth to water from land surface was over a meter greater than at LWPH3). Otherwise, it does not appear that the riparian-zone vegetation in the LCV can adapt quickly enough during the growing season to keep pace with a falling water table induced by regional pumping. The ramifications for the continued existence of the present community of riparian-zone vegetation at the Larned Research Site are significant. If the present riparian-zone vegetation dies out because of an inability to adjust to regional drops in the water table, it will likely be succeeded by invasive species, such as the salt cedar, as has happened in riparian zones throughout semi-arid and arid regions of North America. Further ecohydrologic insights of this type will be developed from the analysis of data in the third year of this project.

Activity 5: Inventory the riparian woodlands of the Arkansas River from Kinsley to Great Bend – the inventory was not done as originally planned because a helicopter inventory of phreatophytes along the Arkansas River corridor was performed by Division of Water Resources personnel. The vegetation patterns resulting from that inventory will be used for the inventory between Kinsley and Great Bend.

Activity 6: Estimate phreatophyte activity along the Arkansas River from Kinsley to Great Bend – an initial estimate of phreatophyte activity was obtained in the latter portions of year two. Data from well LWPH3 were used for this exercise as the fluctuations at that well appear to be representative of the average fluctuations across the LCV (Figure 6). Given an S_Y of 0.20 determined from the analysis of the neutron logs and assuming a riparian zone width of 150 m (a reasonable average for the Arkansas River in this area), the White method was used to obtain an average ground-water consumption of 0.62 m^3/d for 8/26-8/28/02 for a meter-wide strip extending the full width of the riparian zone (Figure 11). This average consumption rate equates to a high-capacity pumping well (defined for this area as a well pumping at 3.79×10^{-2} m^3/s [600 gallons/min]) located every 5.3 km along the river channel. This equivalence should be considered valid only for conditions near the maximum rate of ground-water consumption at the LCV, as the water table was relatively shallow during this period and the amplitude of the fluctuations was relatively large. A complete analysis of the entire data set from the LCV wells will be performed in the third year of this project.

Figure 11
Example Application of White Method
for Calculation of Ground-Water Use
by Phreatophytes for August of 2002.



PAPERS AND PRESENTATIONS

Butler, J.J., Jr., Kluitenberg, G.J., and D.O. Whittemore, A field method for estimation of ground-water consumption by phreatophytes – year one (abstract), Proc. 21st Annual Water and the Future of Kansas Conf., p. 27, 2004.

Butler, J.J., Jr., Groundwater flow in interconnected stream-aquifer systems: From models to the field, an invited presentation to the Department of Geological and Atmospheric Sciences, Iowa State University, March 12, 2004.

Butler, J.J., Jr., Loheide, S.P., II, Kluitenberg, G.J., Bayless, K., Whittemore, D.O., Zhan, X., and C.E. Martin, Groundwater consumption by phreatophytes in a mid-continent stream-aquifer system (abstract), Eos, v. 85, no. 17, Jt. Assem. Suppl., p. JA237, 2004.

Butler, J.J., Jr., and D.O. Whittemore, Recent Kansas Geological Survey activities at the Larned Research Site, presentation to the Board of Ground Water Management #5, Stafford, KS, September 9, 2004.

Loheide, S,P., II, Butler, J.J., Jr., and S.M. Gorelick, A modeling evaluation of a method for estimating groundwater usage by phreatophytes (abstract), GSA 2004 Annual Meeting Abstracts with Program, v. 36, no. 5, p. 390, 2004.

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McKay, S.E., Kluitenberg, G.J., Butler, J.J., Jr., Zhan X., Aufman, M.S., and R. Brauchler, In-situ determination of specific yield using soil moisture and water level changes in the riparian zone of the Arkansas River, Kansas, Eos, v. 85, no. 47, Fall Meet. Suppl., Abstract H31D-0425, 2004.

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INFORMATION TRANSFER

Seven presentations concerning this project were presented at various venues both within and outside of Kansas during year two. Two additional abstracts were prepared in year two for presentations early in year three (Water and the Future of Kansas Conference - March 2005, Kansas Academy of Science Conference - March 2005). One manuscript on a modeling assessment of the White method for estimating groundwater consumption by phreatophytes from water-table fluctuations was submitted to the journal Water Resources Research early in year two and was accepted. The paper should be published in the fall of 2003. Work began on a manuscript describing the results of the field investigation of phreatophyte-induced fluctuations in the water table. This manuscript will be completed and submitted to a scientific journal in year three.

STUDENT SUPPORT

Three students participating in the Applied Geohydrology Summer Research Assistantship Program of the Kansas Geological Survey, one KSU graduate student, and one KSU research assistant were partially supported from this grant during the summer of 2004. These students contributed to the aspects of the project involving well and access-tube installation, water-level and vadose-zone monitoring, sapflow sensors, conductance measurements, and weather-station upkeep. Travel, research supplies, and cherry-picker rental were provided for a KU graduate student to perform the leaf-scale transpiration monitoring.